

## **Acoustic Blind Deconvolution and Frequency-Difference Beamforming in Shallow Ocean Environments**

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### **LONG-TERM GOALS**

The overall long-term goal for this project is to develop engineering tools that are useful to the Navy as it operates in uncertain, partially known, or unknown ocean environments. During the last year, this project has focused on further determining the utility of a fully-passive propagation-physics-based technique for blind deconvolution of array-recorded sounds from a remote source with emphasis on determining how sparse-array measurements might be used for this task.

The long term goals of this project are: *i*) to determine the effectiveness of synthetic time reversal (STR) for the purposes of blind deconvolution in noisy unknown ocean sound channels, *ii*) to effectively apply STR to marine mammal sounds recorded in the ocean with vertical and/or horizontal arrays, and *iii*) to utilize the STR-estimated signals and ocean-sound-channel impulse responses to classify, localize, and/or track individual marine mammals (or other sound sources) of interest.

### **OBJECTIVES**

Since early 2009 this project has focused on developing an acoustic-ray-based version of synthetic time reversal (STR), a fully-passive technique for recovering the original signal and the source-to-array-element impulse responses for a remote unknown sound source in an unknown underwater waveguide [1-4]. The specific objectives are to: *a*) determine STR performance as a function of the signal-to-noise, array size, and array element number using acoustic propagation simulations, *b*) verify these findings with simple airborne- or water-borne acoustic laboratory experiments involving multiple receivers and multiple ray paths, *c*) obtain and process underwater array recordings of remote-but-cooperative sound sources, and *d*) obtain and process marine mammal vocalizations for the purposes of marine mammal localization, tracking, and identification. This research effort extends the prior mode-based version of STR [1] to higher frequencies, smaller receiving arrays, sparse receiving arrays, and sound channels with modal dispersion.

### **APPROACH**

Over the last year, this project has focused on processing acoustic array measurements from three different sets of underwater sound measurements to understand the capabilities and limitations of STR.

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This research is the doctoral thesis work of Ms. Abadi. She is a Ph.D. candidate and is just several months away from completing her Ph.D.

The first data set comes from a laboratory cylindrical-water-tank experiment (1.07 m diameter and depth) funded by the Naval Engineering Education Center and involves three-dimensional multipath propagation (reverberation), signals in the 30 kHz to 100 kHz bandwidth, and recordings from a 16-element receiving array (sampled at 1 MHz per channel). The technical goal with this data set is to determine STR performance with a near-field source, variable array geometry, and fully three-dimensional reverberation.

The primary emphasis of this year's work has been the focused acoustic field experiment (FAF06) conducted in July 2006 off the west coast of Italy. Dr. Heechun Song of the Scripps Institution of Oceanography (SIO) provided this data set and collaborated to produce the results [4]. The FAF06 broadcast signals were composed of channel-probing pulses followed by communication sequences. The current blind deconvolution and beamforming results are developed from probe-pulse broadcasts. The probe pulses were 60-ms-duration cosine-tapered frequency sweeps from 11 kHz to 19 kHz. These pulses were broadcast from a 39-m-deep source downslope 2.2 km to a 16-element vertical receiving array with an element spacing of 3.75 m. The array center depth was 52.8 m. The water column depth at the receiving array was 92 m. At the center frequency (15 kHz) of the broadcast signal pulses, the element spacing was nearly 40 wavelengths. Thus, the receiving array was very sparse, so a novel unconventional beamforming approach was necessary for successful beamforming and subsequent STR blind deconvolution. This novel beamforming technique, currently named frequency-difference beamforming, is based on manufacturing a frequency difference from the bandwidth of the recorded signals via a quadratic product of the measured field's Fourier spectrum at two different frequencies. When the array recordings are temporally well-sampled, this frequency difference may be chosen sufficiently low so that the array is no longer sparse and conventional beamforming is possible at the difference frequency. The technical goal with the FAF06 data set was to determine how well STR performed with high-frequency underwater signals and with a sparse receiving array typical of underwater communication experiments.

The third data set considered during this year's work is from the Arctic Ocean off the north coast of Alaska. It was collected by Dr. Aaron Thode of SIO. This data set includes air-gun pulses from seismic surveying and whale calls recorded on a vertical array with 12 elements. The whale call frequencies range from 100 to 500 Hz and the water depth at the experimental site was approximately 55 meters. The purpose for examining this data set was to determine if STR might be beneficial for efforts to monitor marine mammals. To fully understand and utilize this data set, Ms. Abadi spent the 2012 summer semester, May through August, at SIO as a visiting graduate student and worked directly with Dr. Thode.

## **WORK COMPLETED**

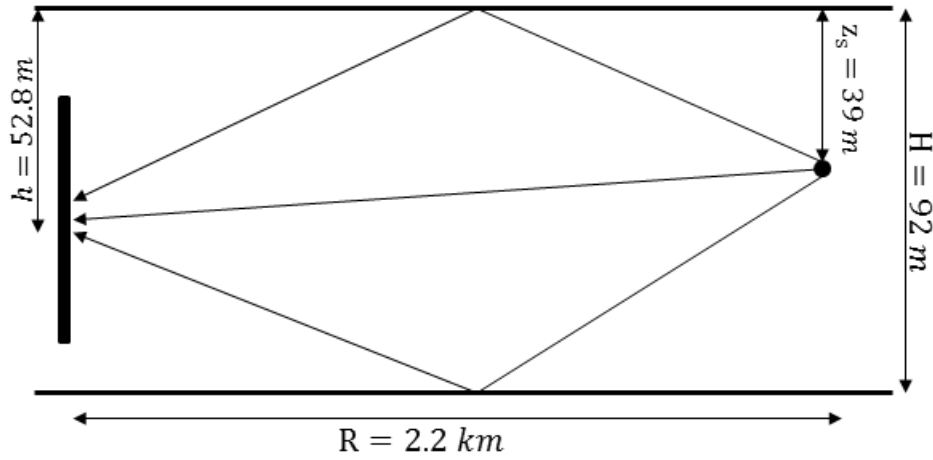
The status of the investigations with the three data sets is as follows.

The research work with the laboratory tank data is underway. Preliminary results are promising. Final results are not yet ready.

The research work with the FAF06 data set is largely complete because the associated technical goals have been met. First, simulations in a simplified version of the FAF06 experimental geometry were

undertaken to refine the unconventional beamforming technique and test STR. This simulation environment is depicted in Figure 1. Subsequent work with the FAF06 measurements achieved intended-broadcast-signal to STR-reconstructed-signal cross correlations above 90%. Interestingly, the unconventional beamforming technique appears to be quite general and may have applications beyond STR blind deconvolution. A paper on these topics has recently been accepted for publication [4].

The research work with the marine mammal data set is well underway. Together Ms. Abadi and Dr. Thode had considerable success simulating the experimental environment, deconvolving whale calls, ranging the calling whales, and developing a means to infer ocean bottom properties from array-recorded remote whale calls. Dr. Thode and Ms. Abadi are currently preparing a journal manuscript on this effort.



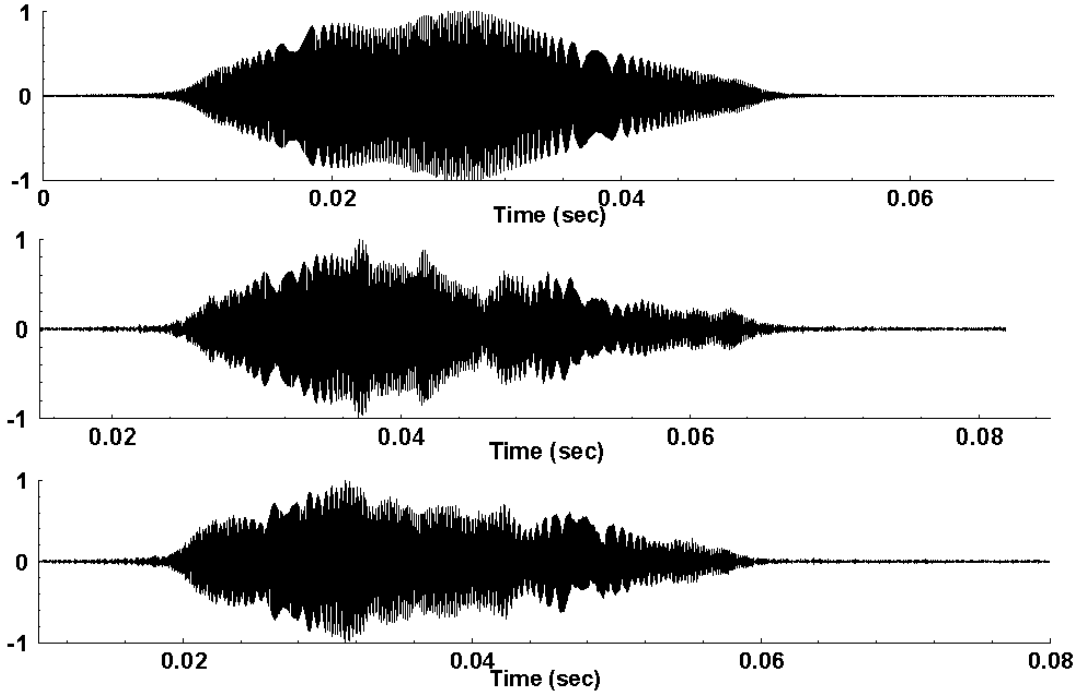
**Figure 1. Simulation geometry meant to approximately mimic the FAF06 sound channel. The signals, receiving array, source depth, source-array range, and sound channel depth at the array match those of the experiment. However, in the simulated environment the sound speed is uniform, the channel is range independent, and only three acoustic paths are considered. In the FAF06 experiment, the sound speed profile was downward refracting, the acoustic propagation was down slope, and more than three acoustic paths were active.**

## RESULTS

To date, this investigation has determined the following about the STR-estimated source-signal waveform using the FAF06 data set. First, the cross-correlation coefficient with the original signal may be at or above 98% for propagation simulations completed in the simplified FAF06 environment shown in Fig. 1. Second, the cross-correlation coefficient with the intended broadcast signal may be at or above 90% using the FAF06 measurements. Moreover, this 90% figure is a conservative number because the FAF06 broadcasts were not monitored with a nearby reference hydrophone, so corrections for the broadcast transducer's phase response could not be made before computing the cross correlation with the STR-estimated source signal. Implementing such a correction would likely increase the final cross correlation values. Sample waveforms are shown in Figure 2. The top waveform is the intended broadcast signal corrected for the broadcast transducer's amplitude response. The middle and lower waveforms are from FAF06 broadcasts that occurred approximately one hour apart. The cross

correlation coefficients between the intended broadcast signal (top) and the two STR-reconstructed signals are 92% and 91%, respectively. The cross correlation between the intended broadcast signal and any of the individual array-element recorded signals (not shown) was typically  $\sim 50\%$ .

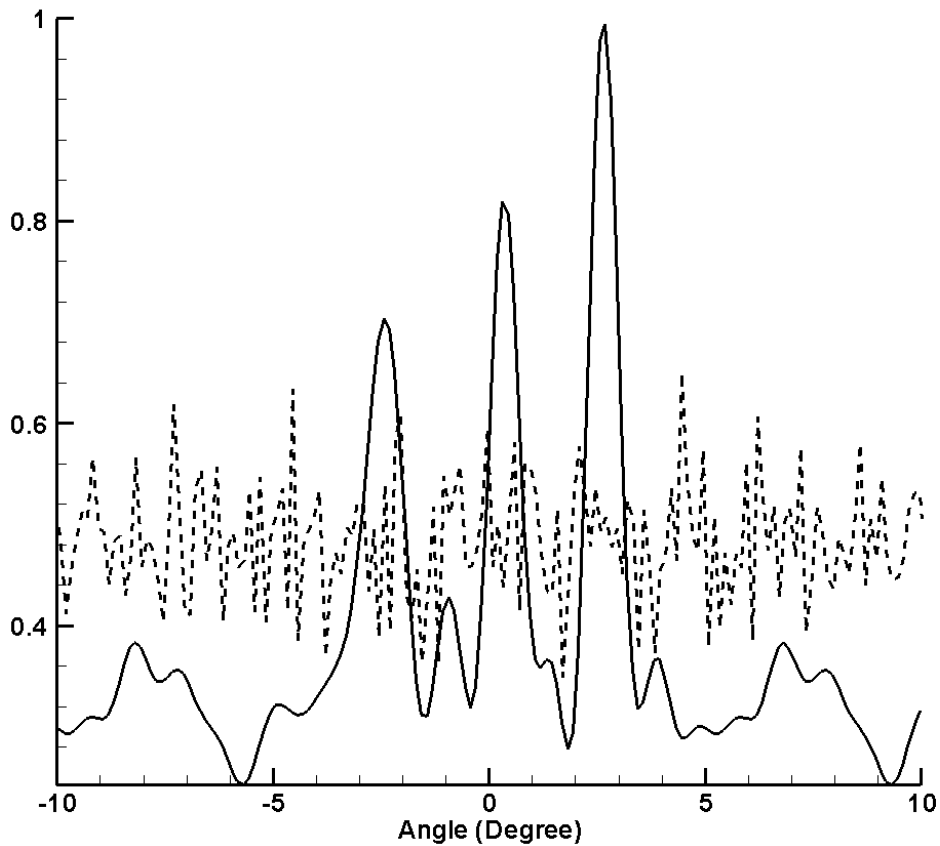
An illustration of the enhanced performance of frequency-difference beamforming is shown on Figure 3, a comparison of conventional beamforming and frequency-difference beamforming results integrated across the bandwidth of the signal for the FAF06 simulations. For this environment and high-frequency signal, the conventional beamforming results are featureless and do not indicate the ray-path directions connecting the source and the receiving array. However, the frequency difference beamforming results with a frequency difference of  $\Delta f = 1562.5$  Hz, which are akin to conventional beamforming at this manufactured difference frequency, are more robust and correctly indicate the ray-path directions. This result is new and unique and it illustrates a direction-finding capability beyond that of conventional beamforming; the broadcast signal did not contain acoustic energy at 1562.5 Hz, yet it can be processed in a manner that extracts information at this frequency from the bandwidth of the signal.



**Figure 2. Reconstructed FAF06 waveforms: (top) intended broadcast signal, a cosine-tapered 60-ms LFM sweep corrected for the projector's amplitude response, (middle) STR estimated source signal using frequency-difference beamforming with  $\Delta f = 12.21$  Hz. The bottom trace is derived from data recorded an hour earlier than the middle trace. The cross correlation coefficients between the intended broadcast signal (top) and reconstructed signals (middle and bottom) are 92% and 91% respectively.**

## IMPACT/APPLICATION

In broad terms, this project ultimately seeks to determine what is possible for a sonar system when environmental information is absent, incomplete, or uncertain. The capabilities of future Naval sonar systems will be enhanced when sonar techniques are developed that do not rely on detailed knowledge of the acoustic environment. Thus, this research effort into the effectiveness and utility of ray-based STR, a relatively-new blind deconvolution scheme, may eventually impact how transducer (array) measurements are processed for detection, classification, localization, tracking, and identification of remote unknown sound sources. The ultimate impact of the novel beamforming technique might be considerable since it allows long sparse arrays to be used for ray-path direction finding. From an array design standpoint, this means that fewer elements may be needed for a given array length, or that a longer array can be deployed for a given number of elements. The extension of frequency-difference beamforming into matched-field processing as a means of increasing its robustness may also have substantial impact on source localization efforts.



**Figure 3. Comparison of conventional delay and sum beamforming output (jagged dashed curve) with frequency-difference beamforming output with  $\Delta f = 1562.5$  Hz (smoother solid curve) vs. beamsteering angle. In both cases the beamforming output has been integrated across the bandwidth of the signal 11 kHz to 19 kHz. The three peaks in the frequency-difference beamforming output correctly identify the three propagation paths in the simulations. The frequency 1562.5 Hz was not broadcast by the remote source.**

## TRANSITIONS

The results of this research effort should aid in the design of sonar signal processing tools for tactical decision aids. However, at this time no direct transition links have been established with more applied research or development programs. Past Navy contacts for this topic with Dr. George B. Smith (NRL-SSC, retired) and Dr. Steve Finette (NRL-DC) are not longer active in this research area. A transition path through NRL or one of the Navy's Warfare Centers is currently being sought.

## RELATED PROJECTS

This project currently uses acoustic array recordings of known man-made sounds that propagated through the ocean. In FY12, such recordings from the Mediterranean Sea were made available by Dr. Heechun Song of SIO. In addition, Dr. Aaron Thode of SIO has provided acoustic array data collected in the Arctic Ocean that includes man-made and marine mammal sounds. The use of blind deconvolution for the recovery of free-field sound source signatures and transfer functions from measurements made in reverberant laboratory test facilities is also of interest for hydro-acoustic testing at the Naval Surface Warfare Center - Carderock Division which is supporting the UM NEEC acoustics student team and the laboratory water-tank experiments mentioned above.

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